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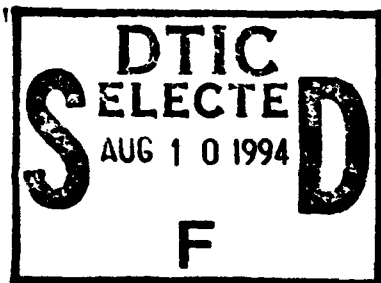
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Water Level and Current Simulation for LOTS Operations – Persian Gulf and Gulf of Oman

by Edward F. Thompson, Zeki Demirbilek,
Lori L. Hadley, Panola Rivers, Karen E. Huff



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by Edward F. Thompson, Zeki Demirbilek,
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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

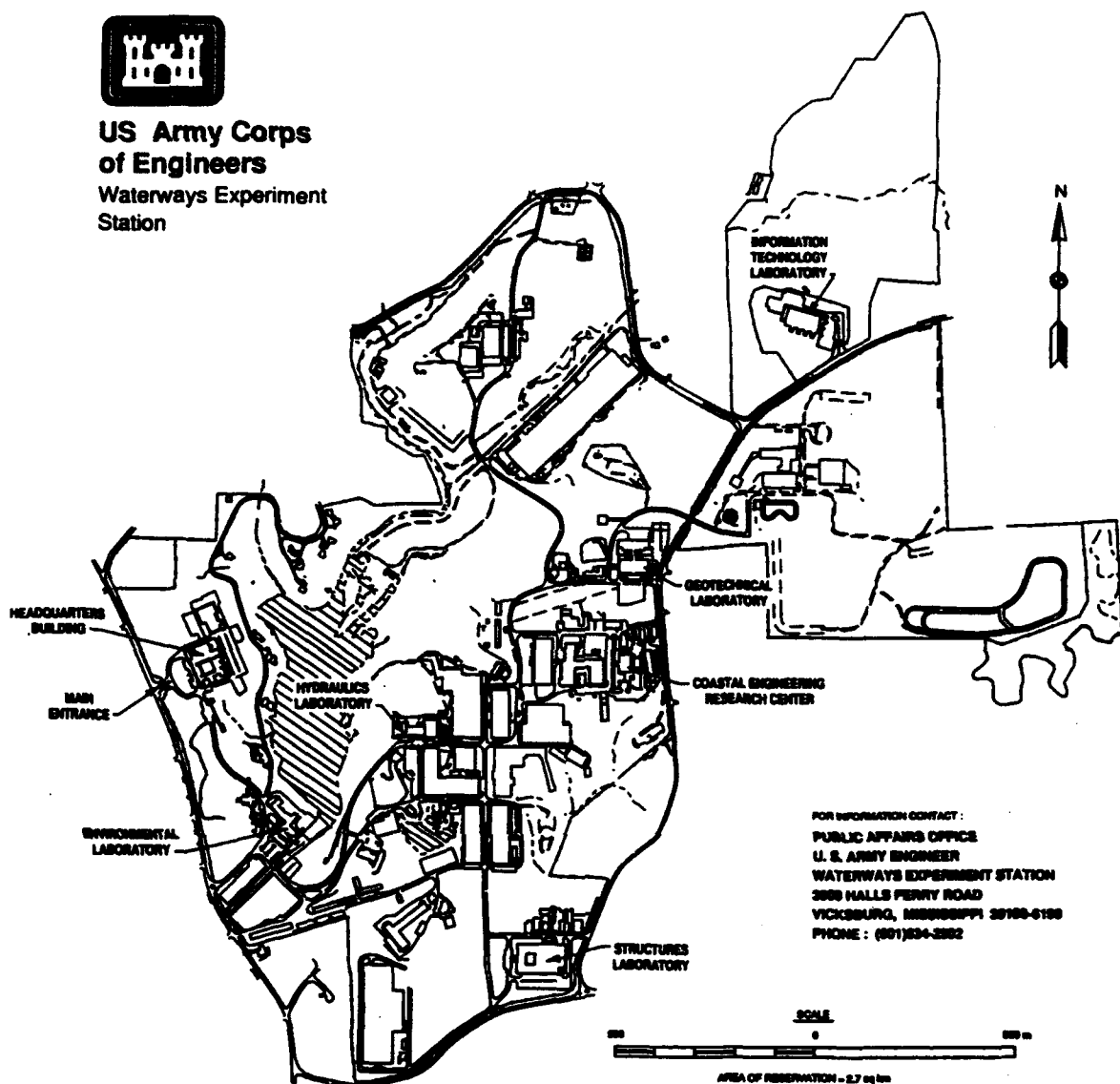
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Preface

The work described in this report was authorized as part of the Military Engineering Research and Development Program, Headquarters, U.S. Army Corps of Engineers (HQUSACE). This report summarizes water level and current investigations performed in the Sustainment Engineering Functional Area, Rapid Damage Repair and Lines of Communication (LOC) Construction Work Package, under Work Unit AT40-RC-004, "Water Levels and Currents for Logistics Over the Shore (LOTS) Operations," at the Coastal Engineering Research Center (CERC) of the U.S. Army Engineer Waterways Experiment Station (WES). Mr. Michael J. Shama was the HQUSACE Technical Monitor, and Mr. Donald D. Henderson was the U.S. Army Engineer Center and School Technical Monitor. Mr. Leonard I. Huskey was the WES Program Manager. Mr. E. Clark McNair, Jr., was the CERC Program Manager, and Dr. Lyndell Z. Hales was the CERC Assistant Program Manager.

This study was conducted from January 1991 through September 1993 by Drs. Edward F. Thompson and Zeki Demirebilek and Mses. Lori L. Hadley and Panola Rivers, all of the Coastal Oceanography Branch (COB), Research Division (RD), CERC, and Ms. Karen E. Huff, formerly of COB. The study was done under the direct supervision of Dr. Martin C. Miller, Chief, COB, and Mr. H. Lee Butler, Chief, RD, and under the general supervision of Mr. Charles C. Calhoun, Jr., Assistant Director, CERC, and Dr. James R. Houston, Director, CERC. Mr. Scott Sherard, formerly of COB, assisted greatly with data preparation, processing, and interpretation.

Tidal gauge data for this study were provided by the National Ocean Service of the U.S. Department of Commerce. Dr. Joannes J. Westerink, Associate Professor, University of Notre Dame, Notre Dame, IN, collaborated closely with the study team during this project. His contributions are greatly appreciated.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Introduction

Background

As part of the Military Engineering Research and Development Program, the U.S. Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), has operated five work units in support of Logistics Over The Shore (LOTS). The primary research objective is to develop a numerical simulation planning model which will assist in maximizing LOTS offloading and throughput operations. The objective is addressed in the following two parts:

- Develop a numerical modeling capability for simulating and summarizing key characteristics of potential LOTS sites within a geographic region
- Develop a numerical modeling capability to forecast and optimize throughput during an ongoing LOTS operation

The work unit Water Levels and Currents for LOTS Operations under which this study was performed contributes to both objectives, providing a key component of the environmental conditions faced in a LOTS operation.

The first work unit to receive funding under the CERC LOTS effort used numerical modeling tools to produce a wind wave climatological summary in the Persian Gulf, an area of potential LOTS operation (Bratos and Farrar 1994). The Water Levels and Currents for LOTS Operations work unit was initiated as a complementary effort to provide an operational numerical model of tidal and wind driven water levels and currents for the same region of potential operation. That effort, the subject of this report, was later accelerated and abbreviated as the work unit objectives expanded to take advantage of an opportunity for field demonstration in the Joint Logistics Over The Shore (JLOTS III) exercise (Thompson and Hadley 1994).

Previous Studies

The Persian Gulf has long been an important water body for economic, environmental, and military reasons (Figure 1). It is a large, shallow basin

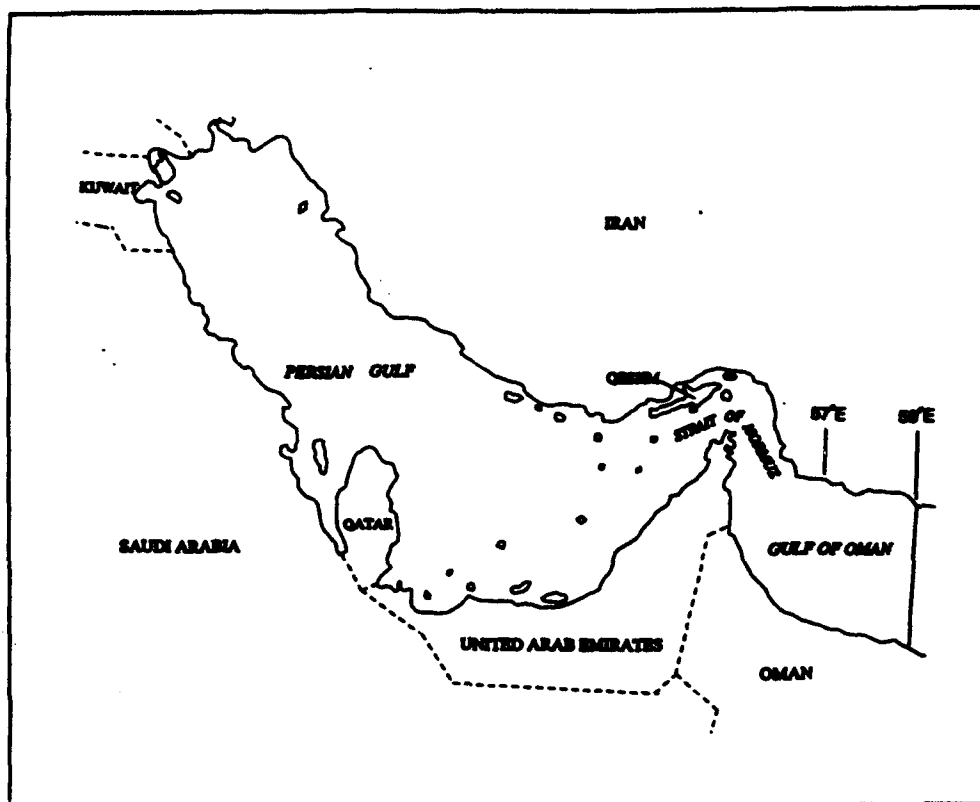


Figure 1. Study location

located in the heart of the Middle East. Its notable importance during recent decades stems from several factors. Countries bordering the Persian Gulf are rich in oil reserves. Consequently there is considerable oil industry shipping through the Gulf as well as a large industry investment in marine drilling and production platforms. Desalinization plants along the Gulf shores provide fresh water for the arid lands in the region. The Gulf is productive biologically, with numerous marsh areas and an active fishery. As a result of these factors coupled with extended political turbulence in the region, a number of previous studies have been conducted. Those most relevant to the present study are reviewed in the following paragraphs.

Astronomical tidal elevations over the entire earth were modeled by Schwiderski (1980). A relatively coarse, uniform spatial resolution of 1 deg in latitude and longitude was used. Accuracy of the model is degraded near land because the coast and shallow shelf areas are poorly resolved. The problem is partially solved by making use of available nearshore measurements to correct the model results. Model estimates in the deeper ocean areas are generally considered to be relatively accurate. Tidal constituents were modeled individually and global results were published in a series of reports (Schwiderski 1979, 1981a-g). The model extends into the Gulf of Oman, taking advantage of measurements along the Omani and Iranian coasts, but it stops short of the Strait of Hormuz.

Tidal characteristics at a number of coastal measurement sites in the Persian Gulf and Gulf of Oman are summarized by the National Ocean Service (NOS) of the U.S. Department of Commerce and the British Hydrographer of the Navy. The NOS annually publishes high and low water predictions and information on tide range (e.g. U.S. Department of Commerce 1990). The NOS archive of tidal measurements includes data from some Persian Gulf stations. The data are in a variety of forms, as discussed in Chapter 3. The Hydrographer of the Navy (1989) provides amplitudes and phases for 4 tidal constituents at many stations dispersed around the Gulf.

Lardner et al. (1986) present an approach for solving the two-dimensional tidal equations by the method of characteristics. The model is applied to the Persian Gulf. Cotidal and corange lines from the U.S. Hydrographic Office and from the model for the M_2 and K_1 constituents are shown and discussed. Cotidal and corange lines are defined as follows (Hicks 1989):

Cotidal line: a line passing through places having the same cotidal hour. Cotidal hour is the average interval between the Moon's transit over the Greenwich meridian and the time of the following high water at any place.

Corange line: a line passing through places of equal tide range.

Cotidal and corange lines are very useful for showing the general tidal response of a large body of water. Tidal constituents in the Persian Gulf develop counterclockwise rotations. The pivotal points for rotation are referred to as "amphidromic points." Semidiurnal constituents have two amphidromic points in the Persian Gulf (Figure 2). The location of these points is about the same for all semidiurnal constituents. Diurnal constituents have only one amphidromic point, more centrally located in the Gulf than those for the semidiurnal constituents.

Bogdanov (1987) discusses tides in the Persian Gulf and presents tidal charts for the M_2 , S_2 , K_1 , and O_1 constituents. His cotidal lines differ from other published results and should be considered suspect. Another two-dimensional model of tidal hydrodynamics, including transport, is given by Chu et al. (1988).

Tidal and wind-driven circulations in the Persian Gulf were modeled by Lardner et al. (1989) and Al-Rabeh et al. (1990), including some discussion of vertical flow structures. Lardner et al. (1989) includes circulation results for a 12.9 m/s (25 knots) wind blowing from the southwest. In Al-Rabeh et al.'s (1990) study, tidal forcing was provided by nine tidal constituents. The constituent amplitudes and phases imposed along the model boundary in the Strait of Hormuz are given. Measured and model constituent amplitudes and phases for surface elevation are listed for six sites along the Saudi Arabian coast. Cekirge et al. (1989) focussed strictly on wind-induced three-dimensional circulation in the Persian Gulf, presenting an example of surface currents in response to a 12.9 m/s (25 knots) wind from the northwest.

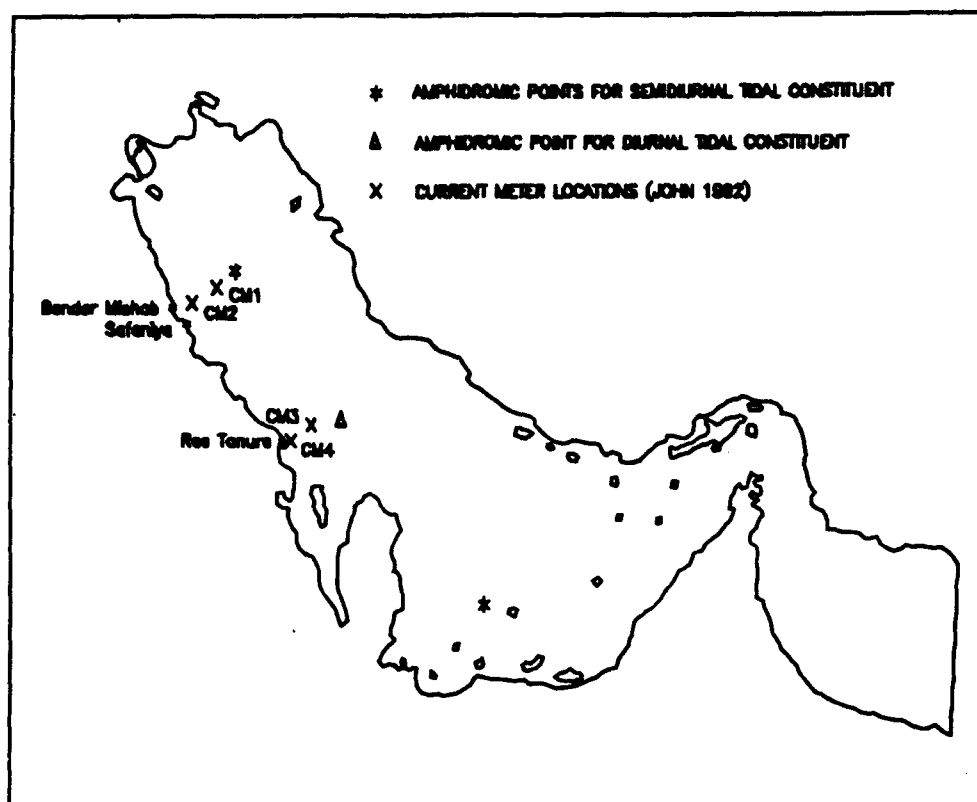


Figure 2. Amphidromic points and tidal current gauge sites

Measurements and harmonic analyses of tidal currents in the western Persian Gulf were reported by John (1992). Gauges were located off the Saudi Arabian coast near Bandar Mishab and Ras Tanura. The gauge sites are in the vicinity of amphidromic points for semidiurnal and diurnal tidal constituents (Figure 2). A total of six gauges was operated at four sites for a time period of one month (Table 1). The hourly vector mean at stations CM1, CM3, and CM4 was separated into north and east components.

Each component time series was subjected to harmonic analysis. Amplitudes and phases are given for the M_2 , S_2 , K_1 , O_1 , M_4 , and MS_4 tidal constituents.

A detailed modeling study of the Safaniya area was conducted by Al-Rabeh and Gunay (1992a,b). Both hydrodynamics and particle dispersion were

Table 1
Tidal Current Gauges
(John 1992)

Gauge	Gauge Depth	Water Depth m
CM1	Near surface	30
CM1	Near bottom	30
CM2	Mid depth	5
CM3	Near surface	30
CM3	Near bottom	30
CM4	Mid depth	5

considered. Tidal constituents obtained from measurements at one site are included.

A climatological record of wind and waves over the Persian Gulf was developed by Bratos and Farrar (1994). The study, covering the years 1973-86, used wind measurements around the gulf to estimate the over-water wind field at 10-m elevation. A numerical wave model, driven by the wind fields, produced wave hindcasts at selected sites around the gulf. Wind and wave information were developed at 3-hr intervals on a uniform grid with 16-km square cells.

Procedure

This report describes the activities and accomplishments done under the Water Levels and Currents for LOTS Operations work unit in modeling the Persian Gulf and Gulf of Oman. It includes significant development of computer software tools as well as specific information for the Persian Gulf area. The numerical model for simulating water levels and currents driven by tide and wind is described in Chapter 2. Computer programs for pre- and post processing are also discussed. Chapter 3 covers the calibration and verification of numerical simulation procedures for water levels and currents.

An example application of the simulation model to a LOTS site is discussed in Chapter 4. Conclusions and recommendations are given in Chapter 5.

2 Water Level and Circulation Model

Governing Equations

The WES numerical model known as the ADvanced CIRCulation model (ADCIRC), Version 8.01, was used in this study for simulating water levels and currents due to long wave hydrodynamic processes. The model is based on the equations of mass and momentum conservation. The equations are integrated over water depth; flows are assumed to be uniform in the vertical dimension. It is additionally assumed that flows are incompressible, vertical accelerations are negligible, and pressures are hydrostatic. Bottom stress is parameterized by a standard quadratic expression. The Newtonian equilibrium potential for astronomical tide is expressed as given by Reid (1990). The influence of wind is represented as a stress applied to the free surface. Other forcing functions are atmospheric pressure gradients, Coriolis effects, and tidal forcing along the seaward boundary.

The WES has published a series of reports developing and documenting the ADCIRC model. The theory and methodology of ADCIRC are described in detail by Luetich et al. (1992). This study used the vertically integrated, two-dimensional ADCIRC model, documented for users by Westerink et al. (1993). Westerink et al. (1993) applied the ADCIRC model to the western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea to develop a comprehensive data base of tidal constituents. The study included a systematic examination of resolution requirements in a triangular mesh, finite element numerical grid. The optimum grid consisted of graded element sizes, with the largest elements in the deep ocean and the smallest near the coast. Site specific applications of the model are given by Westerink et al. (1991), Mark and Scheffner (1994), and Thompson and Hadley (1994). It should be noted that the computational modeling part of this study was conducted earlier than the above cited studies and during a period of very active development of ADCIRC. In fact, several permanent enhancements to ADCIRC were developed under this study. The developmental version of ADCIRC used in this study established the basis for some important refinements of the later versions.

The ADCIRC model equations are solved by a finite element approach. However the equations are reformulated mathematically to a form with much improved numerical solution characteristics. The new form, referred to as the Generalized Wave Continuity Equation (GWCE), is solved for surface elevation and velocity on a standard finite element grid consisting of linear triangular elements. The ADCIRC solution procedure and FORTRAN coding are designed to maximize computational speed and efficiency.

Development of the GWCE approach for shallow water long wave modeling (Lynch and Gray 1979, Kinnmark 1984) was the key to major advances in long wave modeling. The GWCE allows the power and flexibility inherent in the finite element approach to be used in generating stable, accurate numerical solutions which were not possible with the primitive forms of the equations of motion. Very large areas can be modeled over long time periods with coarse resolution in offshore deepwater areas and highly detailed resolution of the coastal boundary and bathymetry in shallow nearshore areas. Seaward and lateral boundary conditions, which are complex and critically affect model results when the boundaries are near the area of interest, can now be far removed from the study area.

The advantages achieved with finite element solutions to the GWCE have particular importance to LOTS. Large segments of the globe can be modeled at once yet very detailed resolution on the scale of a LOTS site can be introduced in coastal areas of interest.

Several processes characteristic of the Persian Gulf are not modeled. The water can develop significant vertical variations in temperature and salinity. This stratification is not expected to be critical to tidal modeling for LOTS exercises in shallow water. Stratification can affect the response to wind forcing. However, strong winds will increase vertical mixing and decrease stratification in the shallow Persian Gulf. The Persian Gulf experiences heavy loss of water to evaporation. This process induces a net inflow into the Persian Gulf, but it is not critical for LOTS purposes. The high evaporation rate, coupled with little fresh water inflow, leads to very high salinity in some areas of the Gulf.

The ADCIRC model offers a wide range of options. Hence it typically requires an extensive input file. In addition to a file defining the numerical grid, there are a number of model option parameters which allow the user to choose among several alternatives. For example, the parameter NOLI is set equal to 2 for bottom friction to be modeled as a quadratic function of velocity or 0 for no velocity dependence. In either case, the bottom friction term has an inverse dependence on local, time-dependent water depth. A number of parameters must be explicitly defined, such as computational time step, number of run days, and bottom friction coefficient. Some other inputs are discussed in the following sections.

Tidal Forcing

The astronomical tide is created by gravitational pull of the moon and sun, and to a much lesser extent other astronomical bodies, on the earth. Since the astronomical bodies have cyclic, predictable motions, frequencies associated with tidal forcing are very predictable. The frequency components are referred to as "tidal constituents." Although NOS identifies 37 tidal constituents in standard analyses of tide data, the great majority of tidal energy at most locations can be represented by a small number of constituents.

Astronomical tides can be modeled in ADCIRC in two ways. One option is to include the tidal potential forcing function acting directly within the Persian Gulf. This function is essential to proper modeling of large regions. However, the Gulf is small enough that the internal tidal potential forcing can be neglected.

Another optional input to ADCIRC is the specification of astronomical tidal forcing on the seaward, or open grid boundary. For each tidal constituent to be modeled, an amplitude and phase must be provided at each node on the open boundary. The constituent frequency is also required.

The primary tidal constituent forcing the Persian Gulf is the semidiurnal principal lunar tide, commonly referred to as the M_2 tide. Amplitudes and phases for the M_2 tide in the Arabian Sea and Gulf of Oman are included in the global tide model results of Schwiderski (1979). Amplitudes and phases at the ADCIRC open boundary nodes were obtained by interpolation of the global model results. The same approach was used to develop the required input for the other seven tidal constituents included in this study. Included are four semidiurnal constituents (with cycles of approximately 12 hr) and four diurnal constituents (with cycles of about 24 hr) (see Chapter 3 for details).

Wind Forcing

Another optional input to ADCIRC is the wind-induced surface stress. The wind effect on water levels and currents at LOTS sites was needed as part of this study. The ADCIRC model requires wind forcing to be specified as the ratio of both horizontal components of wind stress to water density at each node. An atmospheric pressure, expressed as the ratio of pressure to the product of water density and gravitational acceleration, must also be specified at each node. The procedure used to generate the wind input information is discussed further in Chapter 3.

Pre-Processing and Post Processing

Overview

Considerable effort in this study was devoted to developing pre-processing and post processing computer routines for the ADCIRC model. This study was the first inhouse application of the emerging ADCIRC model. The pre-processing features have now been incorporated into ADCIRC and a more formalized pre-processing software package (Turner and Baptista 1993a). Hence they are not discussed in this report.

The ADCIRC model has a variety of output options including time series of surface elevation and horizontal velocity components at user-specified stations. The time interval between successive values in the time series is also user-specified. The time series serve as input to additional programs which analyze and display results. Post processing programs consist of:

- *Least squares analysis*: performs a least squares based harmonic analysis to estimate amplitudes and phases of tidal constituents
- *Time series recreation*: uses tidal constituents to generate a time series, statistical summary, and plot
- *ADCIRC spatial time series analysis*: directly analyzes ADCIRC output over the whole grid domain to get summary information such as tidal ranges and phases

Least squares analysis

The least squares analysis program reads time series of water surface elevation or horizontal current components generated by ADCIRC at given stations. The frequencies of tidal constituents of interest are specified. A least squares fitting procedure is used to estimate the amplitude and phase of each tidal constituent requested. Since current components are processed independently, complete results at a station would include three sets of amplitudes and phases: one for elevations and two for current components. Results are written in a form for input to the time series recreation program.

Typically time series points are saved every 30 min to 60 min for at least 29 days. Time series files are large. However the output files of amplitude and phase are small. By representing a station's tidal response in terms of elevation and current constituents, the station response is distilled into a very small amount of information from which the response can be recreated at any time. This compact representation of station response is critical to the LOTS forecasting program.

Time series recreation

The time series recreation program reads tidal constituent amplitudes and phases for elevation or current components at a station and creates a time series. The beginning time, time interval between points, and length of the time series may all be selected by the user. The beginning time and length of the time series are chosen to coincide with available field measurements. Separate time series are created for the two components of horizontal current.

Water level and current statistics may also be generated. Water level statistics are computed from elevation time series. Statistics which can be computed are:

- Mean Sea Level (MSL): mean of all elevations in the time series
- Mean High Water (MHW): mean of all high water peaks in the time series
- Mean Low Water (MLW): mean of all low water valleys in the time series
- Mean Higher High Water (MHHW): mean value of the highest high water peak on each tidal day
- Mean Lower Low Water (MLLW): mean value of the lowest low water valley on each tidal day
- Maximum high water (HMAX): single highest value in the time series
- Maximum low water (LMAX): single lowest value in the time series

Current statistics include the mean and maximum current and a probability distribution of current speed and direction. The current speed interval in the distribution is user-specified; the direction interval is 22.5 deg.

ADCIRC spatial time series analysis

Direct visual analysis of ADCIRC output time series over the whole grid domain is another extremely useful option. Water level and current variations with time over the Persian Gulf and Gulf of Oman can be viewed as color bands, gray-scale bands, or contour lines using workstation-based visualization software (Turner and Baptista 1993b). The display can also be animated and transferred to videotape.

A special post processing computer routine was written to extract spatial statistical information from the ADCIRC elevation time series. Information computed at each node includes maximum and minimum elevation in the time series, range (difference between maximum and minimum), and time of maximum. When only one constituent and one tidal cycle are analyzed, a phase

difference between the maximum at each node and the seaward boundary maximum can also be computed. The phase difference is translated into degrees for the particular tidal constituent represented. An option is available for shifting phase differences to another reference time, such as the Universal Time Coordinate (UTC), formerly called Greenwich Mean Time (GMT).

Ranges and phase differences are written in a form for input to the visualization software package. Contours of equal range (co-range lines) and phase (co-tidal lines) may then be viewed in multi-color screen displays on an engineer workstation. The images can also be printed.

3 Calibration and Verification

Tidal Water Levels

Before water level and current predictions for the Persian Gulf and Gulf of Oman can be made with confidence, it is critical to insure that the numerical model is properly calibrated and verified. The approach taken was to run the ADCIRC model for a sufficiently long time, save the tidal water level time series at locations where measurements are available, and compare attributes of the computed and measured time series. Adjustments are made to ADCIRC input and the comparisons regenerated until good agreement between model-generated and measured water levels is achieved. The process of calibration and verification is discussed in detail in the following paragraphs.

The ADCIRC model for water levels and currents requires a comprehensive set of input information. A key initial step in applying the model to the Persian Gulf and Gulf of Oman is calibration, which is performed to determine the proper input information. Input includes the grid, external forcing (tide along the seaward boundary and wind over the model domain), and a variety of parameters. Tidal water level information for calibration are available from NOS and the British Hydrographer of the Navy (1989) at a number of coastal locations around the area.

The Gulf of Oman is very deep (over 3000 m) at its juncture with the Arabian Sea. Most of the Gulf of Oman is at least 1000 m deep up to about longitude 57° E (Figure 1) at which point the bottom depths sharply decrease into the Strait of Hormuz. Depths across the Strait of Hormuz are about 50-100 m. The Persian Gulf is quite shallow, with a maximum depth of about 90 m and a mean depth of 35 m. The deeper areas follow the Iranian coast. The southern and western parts of the Persian Gulf and the head, near the Kuwait/Iraq/Iran borders are relatively shallow. Tides in the Persian Gulf are determined by the Gulf's unique hydrodynamic response to tidal forcing through the Strait of Hormuz.

Initial bathymetry for the Persian Gulf and Gulf of Oman was obtained by digitizing a detailed bathymetric contour map from the U.S. Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS. Because of the critical effect of bathymetry on tidal response in this constricted, shallow region, a more refined bathymetric data set was assembled when it became

available. Digital depth information with a resolution of 2 minutes in longitude and latitude was obtained from NAVOCEANO. Computer routines were written to combine information from different 1 deg squares of longitude and latitude to create a bathymetric data file for grid development.

Four grids were developed during the course of this study. Software for semi-automated grid development (Turner and Baptista 1993a) was in an early stage. However, with assistance from the developers, the software was used successfully in this study. The grids represent successive stages of refinement. The initial grid, using a Mercator projection, was relatively coarse. It covered the Persian Gulf and a small part of the Gulf of Oman. Subsequent grids were based on a spherical projection. The next two grids extended to longitude 59° E. Grid 2 contained finer resolution than Grid 1 and the resolution was nearly uniform. Grid 3, referred to as the refined grid, was obtained by refining the Grid 2 resolution in shallow areas (Figure 3). Grid 4, the expanded grid, was derived by extending Grid 2 seaward into the Arabian Sea (Figure 4). Sizes of the refined and expanded grids (i.e. Grids 3 and 4) are summarized in Table 2. Sensitivity studies indicate that the shallow water refinements of the refined grid are necessary to match gauge data. Hence the refined grid was used for subsequent runs.

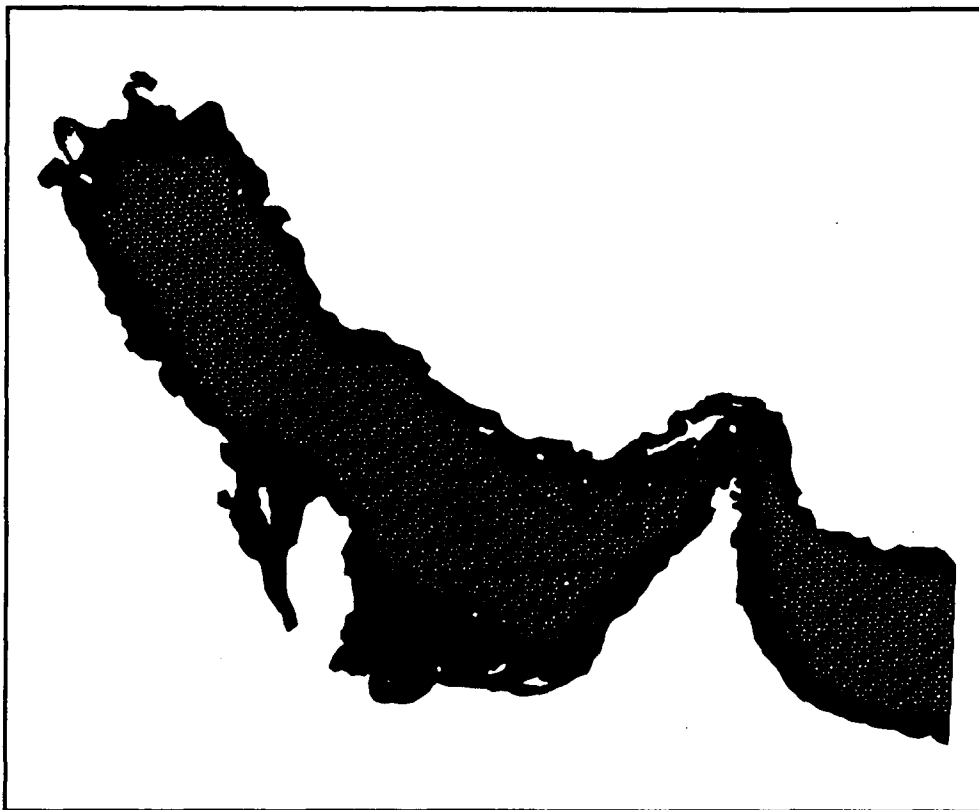


Figure 3. Refined finite element grid

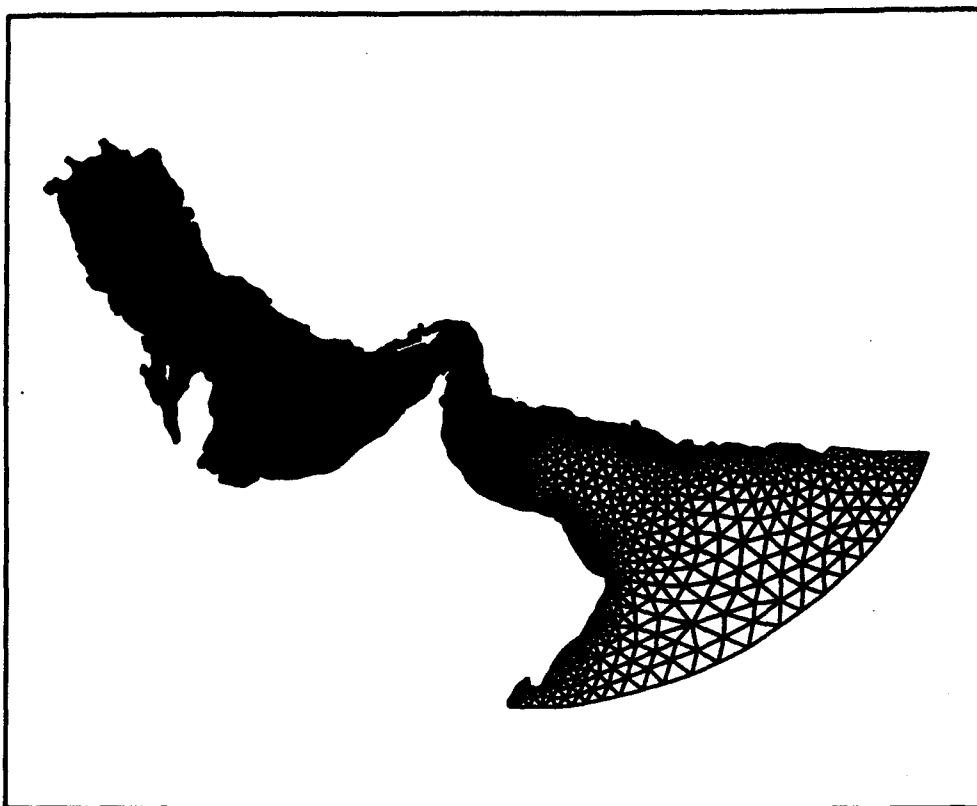


Figure 4. Expanded finite element grid

Table 2 Grid Size		
Item	Size	
	Refined Grid	Expanded Grid
Number of elements	11129	5797
Number of nodes	5947	3248

In this study, as with Westerink et al. (1993), Thompson and Hadley (1994), and Mark and Scheffner (1994), eight constituents were modeled (Table 3). Amplitude and phase for each constituent must be specified at each node on the seaward grid boundary. Amplitude and phase values were derived by spatial interpolation from the published results of Schwiderski, described in Chapter 1. Amplitude and phase values based on those given by Al-Rabeh et al. (1990) at the Strait of Hormuz were also tested, but Schwiderski's values were better documented and gave better results. Phases must be adjusted to represent the beginning date and time for simulation when modeling specific events. Adjustment was not necessary in this study.

Table 3 Tidal Constituents Modeled		
Symbol	Type	Frequency rad/sec
K_1	Diurnal	0.000072921158358
O_1	Diurnal	0.000067597744151
P_1	Diurnal	0.000072522945975
Q_1	Diurnal	0.000064958541129
M_2	Semidiurnal	0.000140518902509
S_2	Semidiurnal	0.000145444104333
N_2	Semidiurnal	0.000137879699487
K_2	Semidiurnal	0.000145842317201

Data for 15 tidal gauge sites in the Persian Gulf were obtained from NOS. Gauge sites were all in the vicinity of the Saudi Arabian coast, a limited part of the Gulf. Data were in the form of hourly surface elevations, high and low water elevations, and/or tidal constituent information. A computer program for generating time series plots and summaries from NOS data was written and used for preliminary evaluations of model results. The program includes options for adjusting the datum, treating gaps in the data, and modifying units of measurement.

Information on four major tidal constituents is also available at many Persian Gulf stations from Admiralty Tide Tables (Hydrographer of the Navy, 1989). Five of the Admiralty stations appeared coincident with NOS gauge sites. Constituent amplitudes and phases at these locations were compared. In all but one case, the NOS and Admiralty amplitudes and phases were very similar.

A calibration set of 12 stations was selected, including many of the NOS stations and a few Admiralty stations to give adequate coverage over the Persian Gulf (Figure 5). The calibration procedure was to run ADCIRC to generate a sufficiently long time series from which constituent amplitudes and phases could be extracted and compared with station results. Much of the calibration phase was aimed at properly modeling the dominant M_2 tidal constituent. A 5-day time series, including a 1-day ramp, was considered adequate for runs with single constituents. Key parameters of ADCIRC were then adjusted until a satisfactory agreement between model and gauge results (primarily the M_2 constituent) was achieved. Some ADCIRC parameters of greatest concern during calibration, and their final values, are given in Table 4.

Significant effort was required to determine proper values for ADCIRC input parameters because of the developmental stage of the model and the unique features of the study area. The approach was to select initial values

comparisons with measurements were achieved. The parameters shown in the table are those with particular significance in this study. A 60-sec time step was needed to insure stable solutions. The ramp time parameter is needed for the model to slowly increase tidal amplitudes specified on the seaward boundary. The ramping helps to minimize spurious oscillation modes created when starting a simulation from static flow conditions.

Elevation time series generated by ADCIRC were analyzed with the least squares fitting procedure, which produces an amplitude and phase for each constituent requested. If ADCIRC is run with a single constituent, then the least squares program is set to identify only that constituent. If ADCIRC is run with all eight constituents, the least squares program provides estimates for all eight constituents.

The final calibration for the single constituent M_2 is shown in Figures 6 and 7. Results for the other constituents were similar. Station numbers are defined in Figure 5. Stations 6 and 12 are omitted because of questions or incomplete information in the measured data.

After calibrating and testing the model for single constituents, the model was tested for two, four, and, finally, eight simultaneous constituents. The progressive testing was necessary to insure the model was working properly. In the final calibration runs, using eight constituents, a 120-day time series with 1-day ramp was generated with ADCIRC. The time series, less the first 5 days for initial spin-up, was analyzed with the least squares program to extract constituent amplitudes and phases. Results were quite satisfactory, comparable to the individual constituent runs (Appendix A).

The ADCIRC model can also provide output information at every node, rather than at a few selected stations, as discussed in Chapter 2. The model was run for single constituents to generate co-range and co-phase lines for the four Admiralty constituents. Co-range plots for the M_2 and K_1 constituents are given in Figures 8 and 9. Plots for the other semidiurnal and diurnal constituents are similar in form.

Figure 8 shows the M_2 tide amplitude decreases during passage through the main Strait of Hormuz. However the tide wave is partially trapped in the narrow, shallow passage between Qeshm Island and the Iranian shore, leading to a local increase in tide range. Model results show the main tide wave propagates westward and northwestward through the deeper portion of the Persian Gulf near the Iranian shore after transiting the Strait of Hormuz. The wave splits north and a little east of Qatar. One arm curves southward toward Qatar and rotates counterclockwise back along the United Arab Emirates toward the Strait of Hormuz. The other arm continues west and north along the Iranian coast into the upper reaches of the Gulf. It curves counterclockwise near the head of the Gulf and continues southeast along the Saudi Arabian coast. As shown in the figure, the Persian Gulf contains two points of rotation, or amphidromic points, for the M_2 tide. The tide range near amphidromic points is

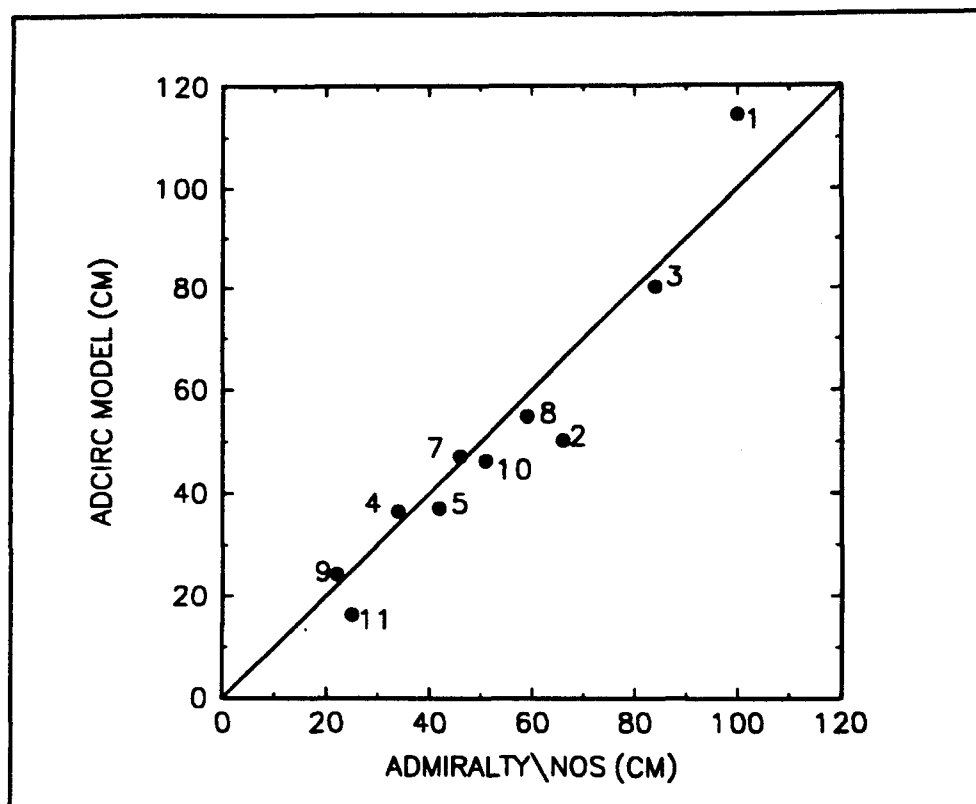


Figure 6. Final calibration for single constituent M_2 , amplitude

relatively low. These results are more detailed but generally comparable to other published results (Lardner et al. 1986).

The diurnal constituents, illustrated with the K_1 constituent in Figure 9, split after passage through the Strait of Hormuz. One arm propagates south to the coast of the United Arab Emirates. There is no amphidromic point formed. The other arm continues toward the northwest along the Iranian side of the Persian Gulf. It develops a counterclockwise rotation and propagates south along the Saudi Arabian coast. The amphidromic point is located north and slightly west of Qatar.

Total tide range over the Persian Gulf was roughly approximated by running ADCIRC with all eight constituents for 15 days. A longer time period would be desirable, but the output file size quickly becomes difficult to manage. An approximate tide range was calculated as the difference between maximum and minimum elevation at each node. No special attention was given to spring/neap tides. Thus results give only an approximate representation of the combined effect of eight tidal constituents on the Gulf (Figure 10). Tide range is relatively small in areas of amphidromic points, basically across the mid portion of the Persian Gulf. The largest ranges occur at the head of the Gulf (around the juncture of Kuwait, Iraq, and Iran) and in the constricted area between Qeshm and the Iranian mainland. These results are very approximate and are best interpreted in a relative sense. In comparison with tide ranges extracted from U.S. Department of Commerce (1990), the absolute

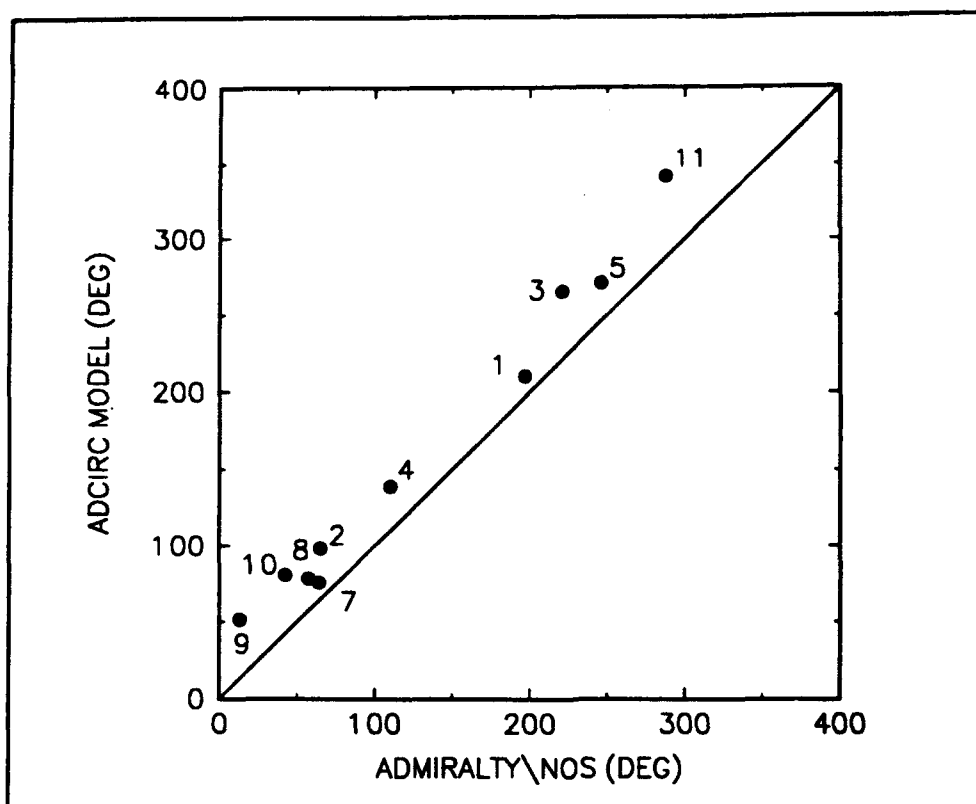


Figure 7. Final calibration for single constituent M_2 phase

model results appear low. NOS tide ranges are taken directly from measurements. Hence they include contributions from all tidal constituents, not just the eight constituents chosen for modeling.

Tidal Currents

Model estimates of tidal current are easily generated along with tidal elevations. However it is more difficult to validate the current estimates. Currents typically vary over short distances and can also vary significantly between the water surface and bottom. Coastal measurements can be strongly affected by even moderately light winds. Suitable current data for comparison with model estimates are much less available than elevation data. Therefore the objective of the tidal current comparisons was to achieve at least an approximate validation of the model estimates. Model parameters were used as established in the tidal elevation calibration.

Tidal current time series at three gauge sites (John 1992) over a 45-day time period were generated with ADCIRC. The time series were analyzed with the least squares fitting program (in the same way as elevations) to generate constituent amplitudes and phases for the north/south and east/west components. North/south and east/west components were processed separately. Constituents were then compared to those given by John (1992) (Figures 11 and 12). The measured values plotted are from gauges nearest the surface for

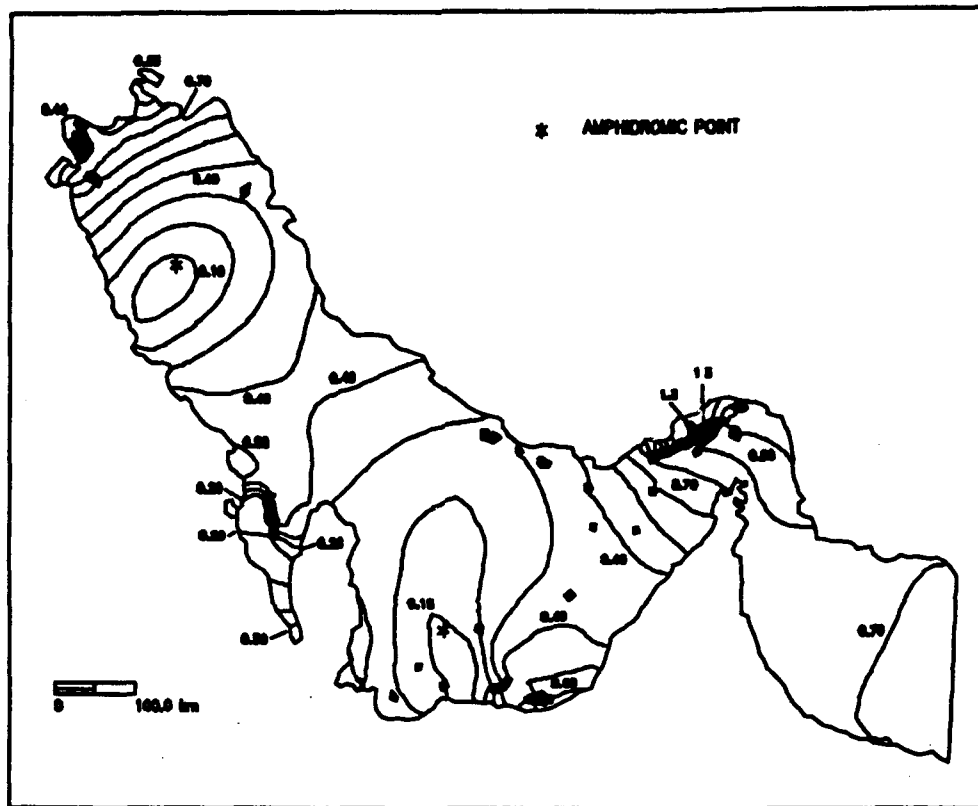


Figure 8. Co-range lines, M_2 constituent, in meters

CM1 and CM3. The deeper gauges gave lower constituent amplitudes. For example, the M_2 amplitudes in the east-west direction are 25.0 cm/sec and 20.5 cm/sec at the upper and lower CM1 gauges, respectively. Phases varied between the upper and lower gauges, with differences ranging from 4 deg to 75 deg. The relatively large overprediction of the M_2 and S_2 amplitudes at CM4 in Figure 12 may be due to lack of detailed bathymetric information in the model at this shallow, fairly complex site. Given the approximations involved in characterizing currents with a vertically-integrated model, the model estimates are reasonably consistent with measurements of both amplitude and phase.

Wind Effects

Winds are a significant component of the Persian Gulf climate. Not only are winds common, but also they can strongly impact water levels and currents in this shallow water body. The "Shamal," an Arabic word for "north," is a persistent wind from the north and northwest. It blows almost constantly during summer and more intermittently, but more violently, during winter. Winds tend to be steered by the mountainous topography, coming more from the west and southwest in the southeastern Persian Gulf region.

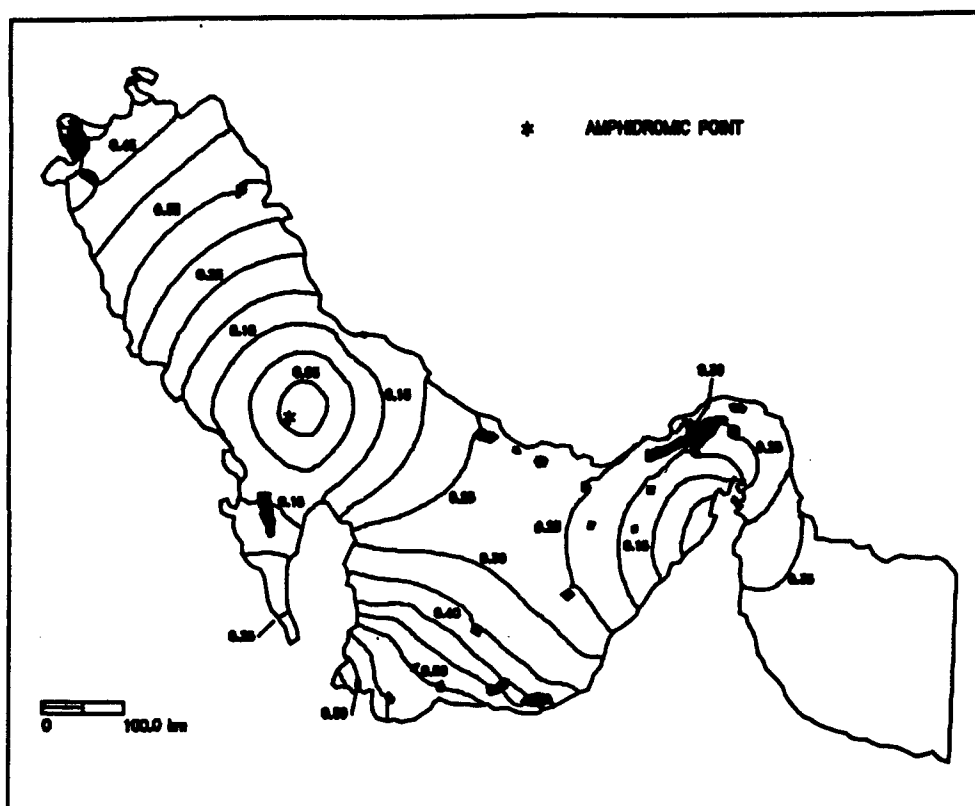


Figure 9. Co-range lines, K_1 constituent, in meters

Sea breeze circulations, induced by temperature differences between land and water, are often significant near the coast.

The ADCIRC model requires wind forcing to be specified as the ratio of both horizontal components of wind stress to water density at each node. A nondimensional atmospheric pressure must also be specified at each node. Procedures for computation of wind stress are discussed by Demirbilek et al. (1993). For this study, a simple, expedient relationship between wind velocity and wind stress was taken from the *Shore Protection Manual* (1977, p. 3-122) as follows:

$$\frac{\tau_{sx}}{\rho} = k W^2 \cos \theta \quad (1)$$

$$\frac{\tau_{sy}}{\rho} = k W^2 \sin \theta$$

where

τ_{sx}, τ_{sy} = horizontal wind stress components

ρ = water density

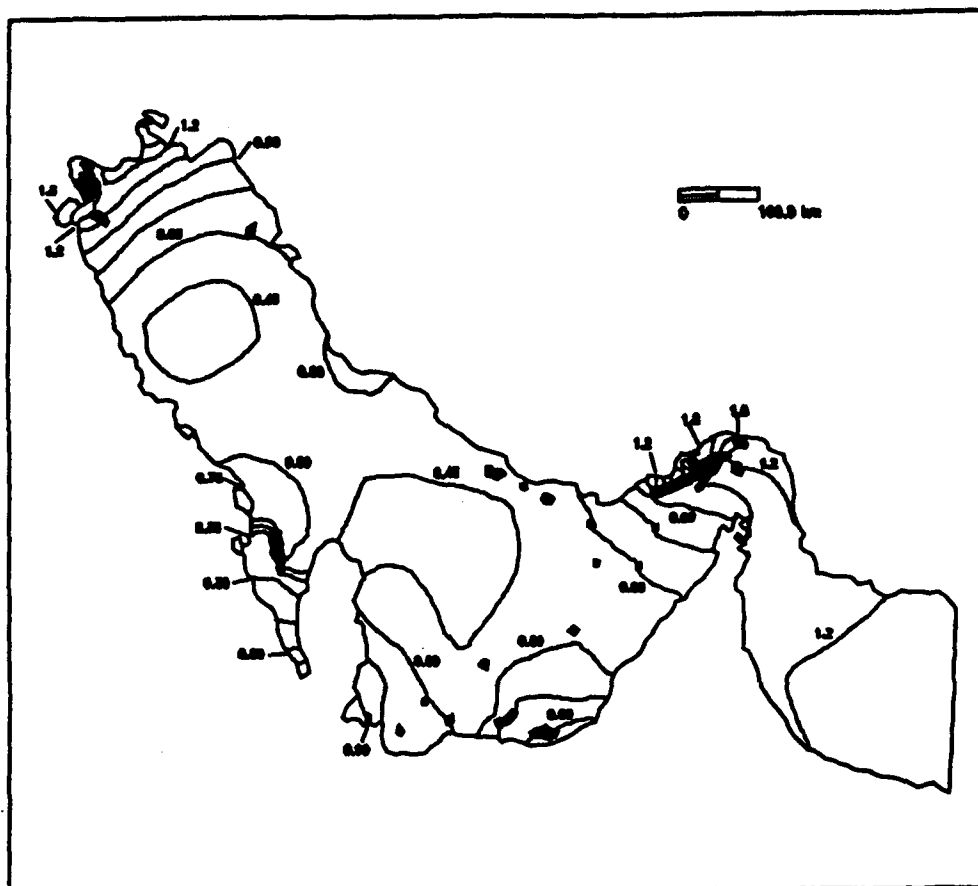


Figure 10. Tide range, eight constituents combined, in meters

k = dimensionless surface friction coefficient

W = wind speed

θ = angle between the x-axis and local wind vector

The coefficient k is assumed to be a function of wind speed and may be given by (Van Dorn 1953)

$$k = 1.1 \times 10^{-6} \quad \text{for } W \leq 7.2 \text{ m/s} \quad (2)$$

$$k = 1.1 \times 10^{-6} + 2.5 \times 10^{-6} \left(1 - \frac{7.2}{W} \right)^2 \quad \text{for } W \geq 7.2 \text{ m/s}$$

Model circulation results for a uniform wind blowing over the Persian Gulf are available in the literature (Lardner et al. 1989). The model wind speed was 12.9 m/s (25 knots) blowing from the southwest. Using the above equations, this wind condition corresponds to

$$W = 12.9 \text{ m/s} \quad (3)$$

$$\theta = 45^\circ$$

$$\frac{\tau_{xx}}{\rho} = \frac{\tau_{yy}}{\rho} = 0.000185 \text{ (m/s)}^2 \quad (4)$$

The same wind condition was imposed in ADCIRC with no tidal forcing. Water surface elevations after the water adjusted to an equilibrium with the wind are given in Figure 13. It is noted that this run was done with the initial grid rather than the detailed grid used elsewhere in this report. The water surface of the Persian Gulf drops along the west and southwest coasts, particularly in the relatively confined areas west and east of the southern coasts of Qatar. The decrease in water level is significant, more than 0.5 m in some areas. Water flows out through the Strait of Hormuz. A raised water level occurs on the north side of the Strait.

The ADCIRC model can be easily used to investigate the simultaneous effect of tides and winds. Strong winds can have a dominant effect on both water levels and currents. The effect of mild winds on coastal water levels is generally smaller than the effect of tides. However, nearshore currents can be strongly influenced by even low wind conditions. Wind-driven currents are particularly important for estimating drift over time periods longer than the tidal cycle, since tidal ebb and flood currents tend to cancel each other.

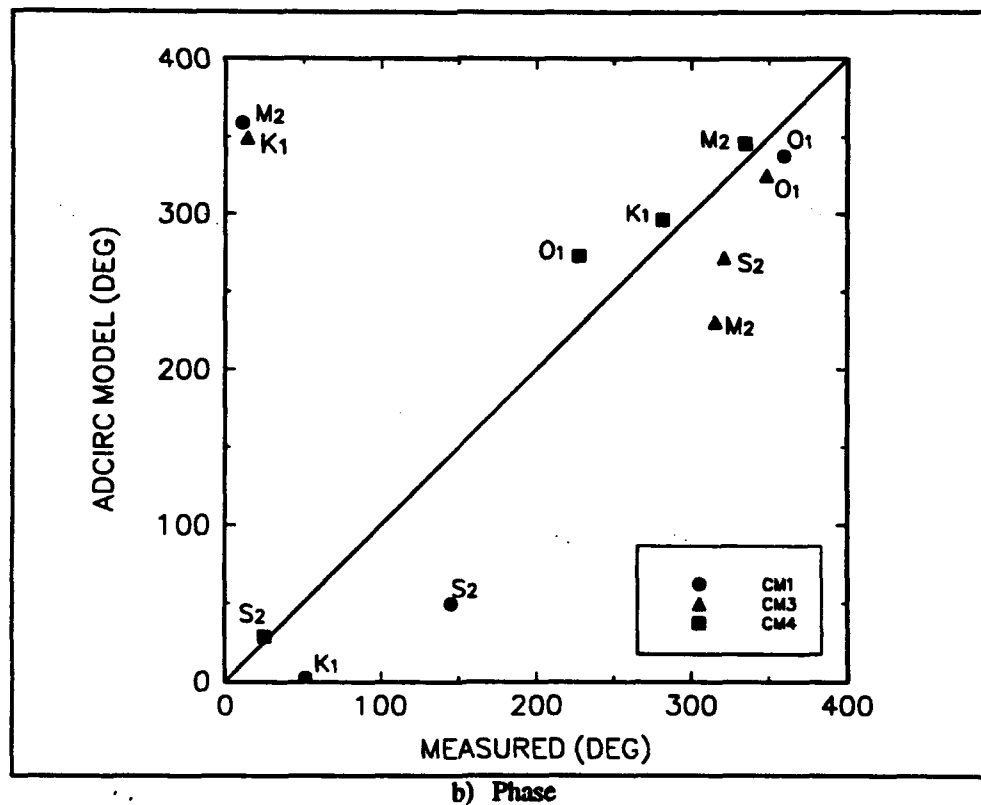
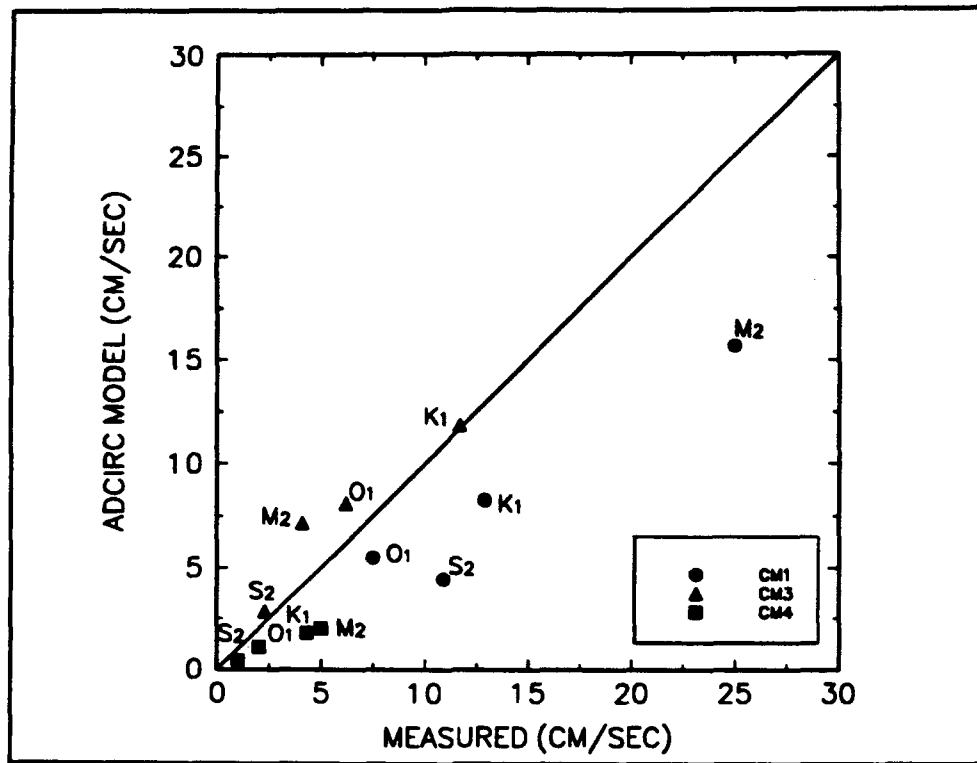
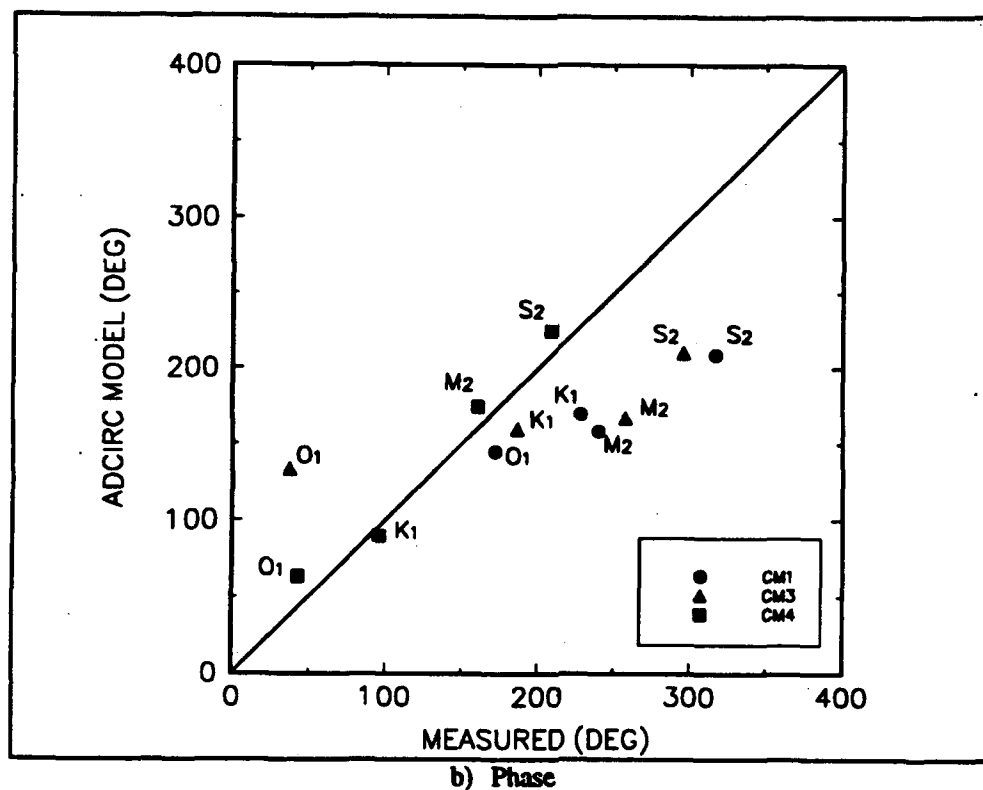
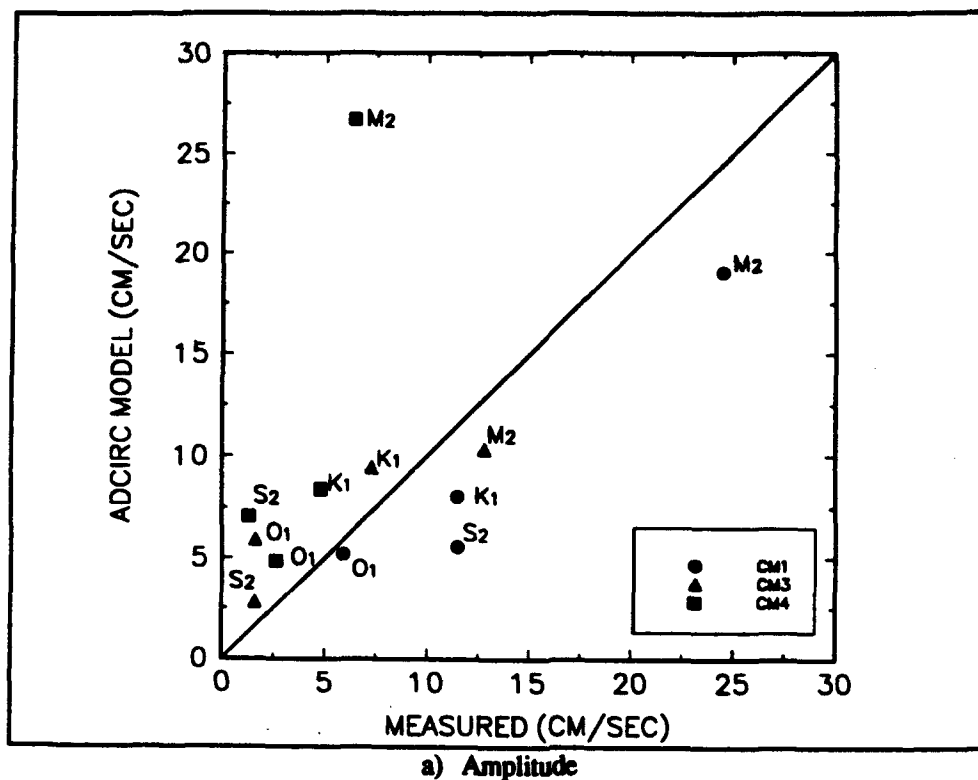


Figure 11. Comparison with current measurements of John (1992), north-south direction



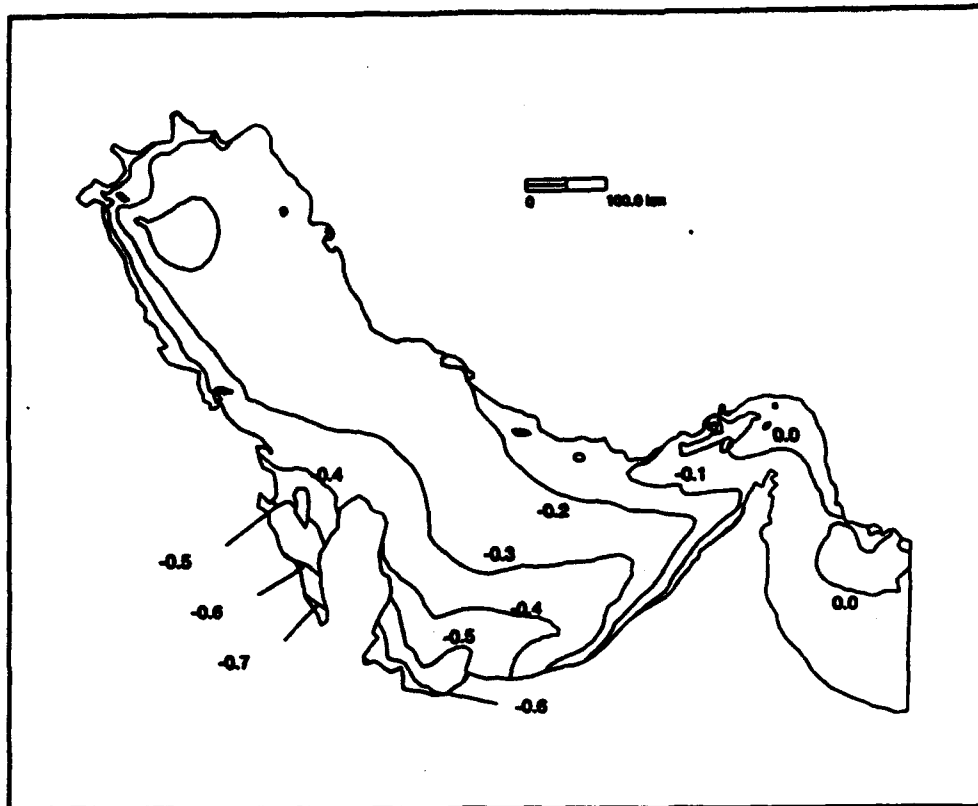


Figure 13. Surface elevation change due to constant wind, 12.9 m/s from the southwest, in meters

4 Example LOTS Application

In addition to modeling water levels and currents over the Persian Gulf and Gulf of Oman, a study objective was to provide a capability for detailed modeling at an example LOTS site. A LOTS operation could occur along a segment of coast less than 10 km in length. Knowledge about currents and water levels within that area is needed. Because currents and, to a lesser extent, water levels can vary considerably over a 10-km coastal reach, the model must be able to achieve detailed resolution at sites of interest.

The level of detail needed at a complex LOTS site cannot be uniformly applied over a large area such as the Persian Gulf. The model grid would be far too large. Originally, this study was planned to develop two grids: a coarse grid resolving the Gulf, and a fine grid in the immediate vicinity of an example LOTS site. Results from the coarse grid would be used as boundary conditions to drive the fine grid. With the emergence of the ADCIRC finite element model, it became possible to incorporate large variations in resolution within a single grid. Thus the capability for detailed resolution at specific sites is inherent in the modeling approach used in this study. The ultimate level of refinement used in a LOTS study will be dictated by military requirements.

The detailed grid developed for this study concentrates elements in areas of shallow depth or areas experiencing high velocities. Model velocity vectors in the central Persian Gulf region illustrate the resolution and increased flows around islands and irregular coastal areas (Figure 14). Even this resolution is relatively coarse compared to the scale of a LOTS site.

Resolution appropriate for a LOTS site is illustrated in Figure 15. Small grid elements were used in this area to capture the strong velocities between the island of Qeshm and the Iranian coast. The flows vary greatly in space and time. Grid resolution could easily be further increased as needed and warranted by knowledge of bathymetry.

Figure 15 shows model velocity vectors at an instant in time. The model also provides water level variation with time. This type of information is needed to predict throughput during an ongoing LOTS operation. A preliminary capability for producing a 3-day forecast of hourly water levels and currents was developed and demonstrated at JLOTS III (Thompson and Hadley 1994). The approach is based on the use of the ADCIRC model to determine

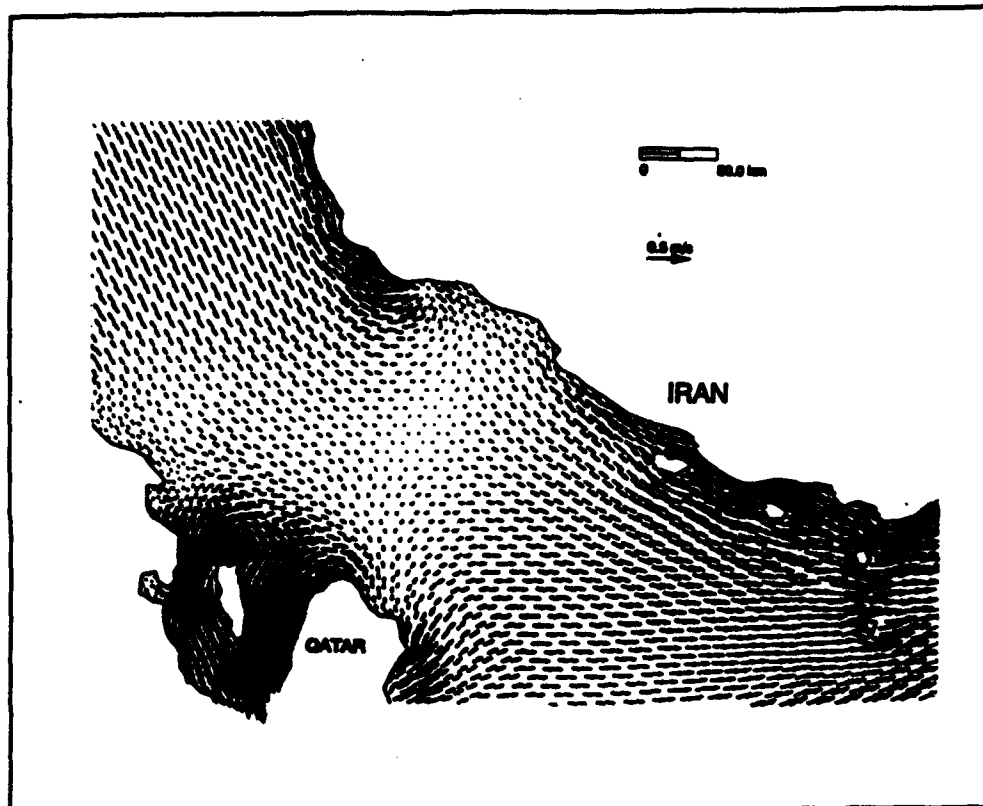
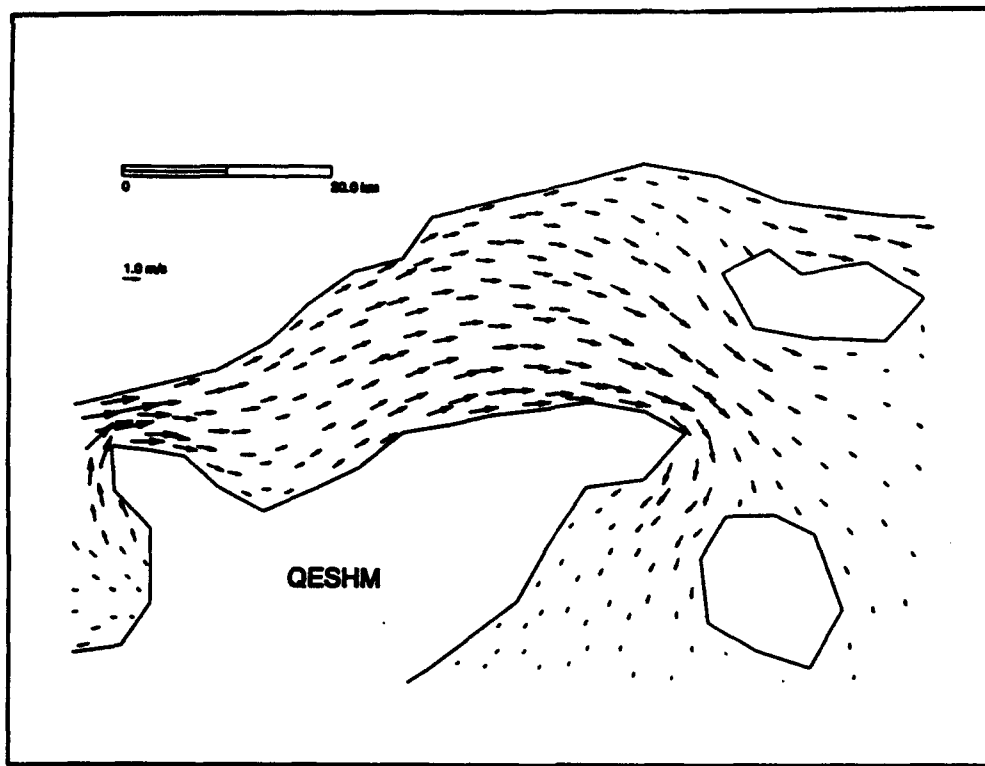


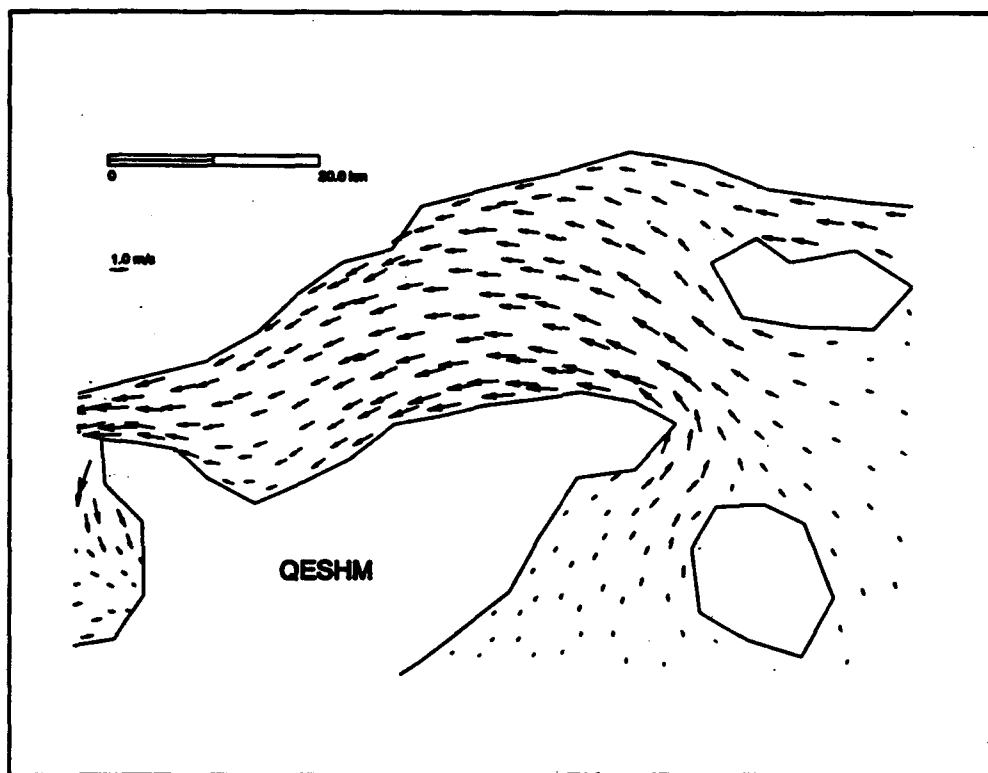
Figure 14. Current snapshot of central Persian Gulf, M_2 constituent

tidal constituents at key locations in the LOTS area of operation. The ADCIRC model is also used to estimate the response characteristics of the LOTS area to winds. Tidal and wind results from ADCIRC are incorporated into the forecasting program.

Climatological information on water levels and currents is also needed in relation to LOTS. The information, along with many other factors, aids commanders in selecting optimum sites for LOTS operations. Thompson and Hadley (1994) discusses and demonstrates the use of tidal constituents and wind response characteristics of the site, both generated by ADCIRC, to provide statistical information on water levels and currents at candidate sites. Wind climate data is a required input.



a) Ebb tide



b) Flood tide

Figure 15. Detailed currents on a scale for LOTS, vicinity of Qeshm Island, same case as Figure 14

5 Conclusions and Recommendations

New technology for detailed numerical modeling of water levels and currents at potential LOTS sites was developed and demonstrated in the Persian Gulf and Gulf of Oman. This technology offers great potential for systematically developing large-scale regional models which are driven by operational global scale tide and wind models. Nearshore areas of special interest, including complicated areas with shoals, islands, and channels, can be represented with exceptional detail and accuracy (provided bathymetric data are available).

The grid used in this study was designed to concentrate resolution in shallow areas or constricted regions where strong flow velocities can be expected. There was no effort to increase resolution at a specific, hypothetical LOTS site. An example LOTS application is discussed in terms of the Iranian coast near the island of Qeshm, where large tides and strong flows are experienced in a confined area. Water levels and currents are estimated with the long wave hydrodynamic model ADCIRC. The model is applied in the following two ways:

- a.* Force with astronomical tides to create tidal constituent amplitudes and phases for water levels and currents.
- b.* Force with wind field to estimate water level and current response.

The model provides information over the entire Persian Gulf as well as detailed information in areas of fine grid resolution. Thompson and Hadley (1994) discusses follow-on programs developed for JLOTS III to combine the tide and wind effects on water level and current and produce information in a form to assist in the following:

- a.* Selecting optimum sites for LOTS operations.
- b.* Forecasting throughput during a LOTS operation.

This study had several limitations. The latest versions of the ADCIRC model and grid development technology are very powerful tools in relation to LOTS applications. However the versions available during this study were in an early stage of development. As a result, the accuracy and flexibility of the study was limited. Further, the Persian Gulf study was accelerated and abbreviated so that the original study objectives could be expanded to include the JLOTS III field exercise.

Based on this study and the related study by Thompson and Hadley (1994), the following recommendations are made:

- a.* Water levels and currents in the Persian Gulf and Gulf of Oman should be given further consideration to include the following enhancements to the present study:
 - (1) An updated version of the ADCIRC model should be used.
 - (2) The detailed grid should be extended into the Arabian Sea to ensure that tidal forcing on the seaward boundary is free of distortions induced by shallow water and land.
 - (3) The grid should be modified to include detailed resolution in areas of potential LOTS interest.
 - (4) Effects of vertical variation in currents should be considered.
 - (5) Wind forcing should be studied in more detail, including more complete verification and coupling with the wind fields of Bratos and Farrar (1994) to estimate climatological water levels and currents.
- b.* Large regions (on a scale at least as large as the Persian Gulf and Gulf of Oman) should be defined and modeled for all coastal areas of the world which have potential for LOTS activity.

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Appendix A

Tidal Constituent Amplitudes and Phases

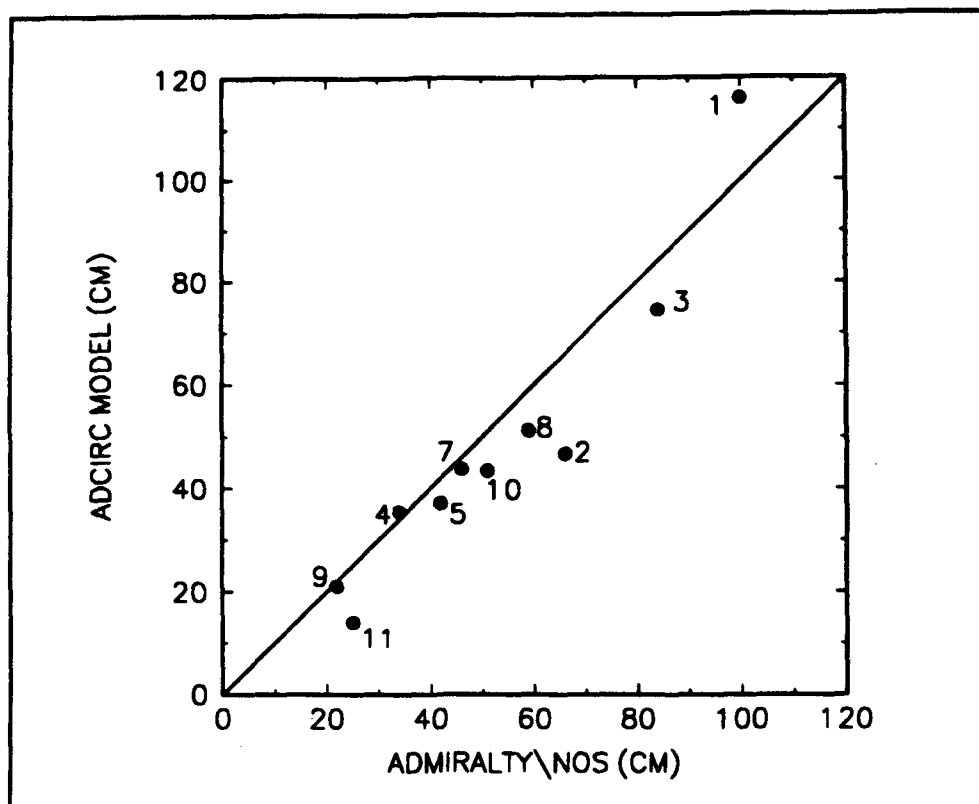


Figure A1. M_2 tidal constituent amplitudes

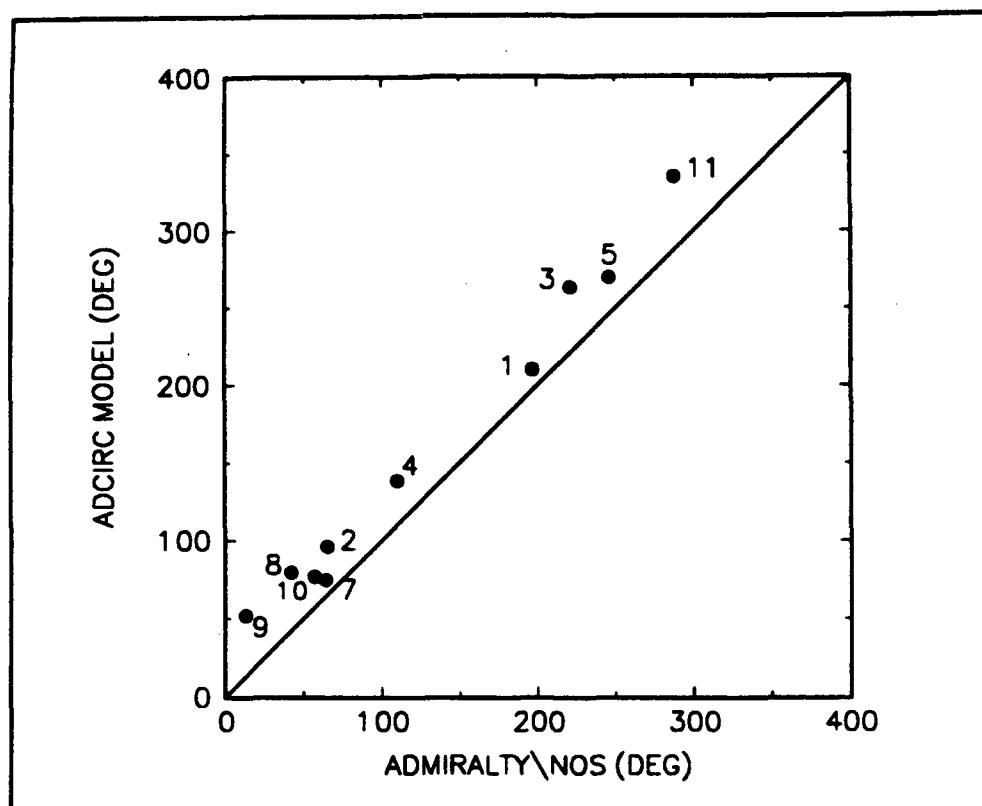


Figure A2. M_2 tidal constituent phases

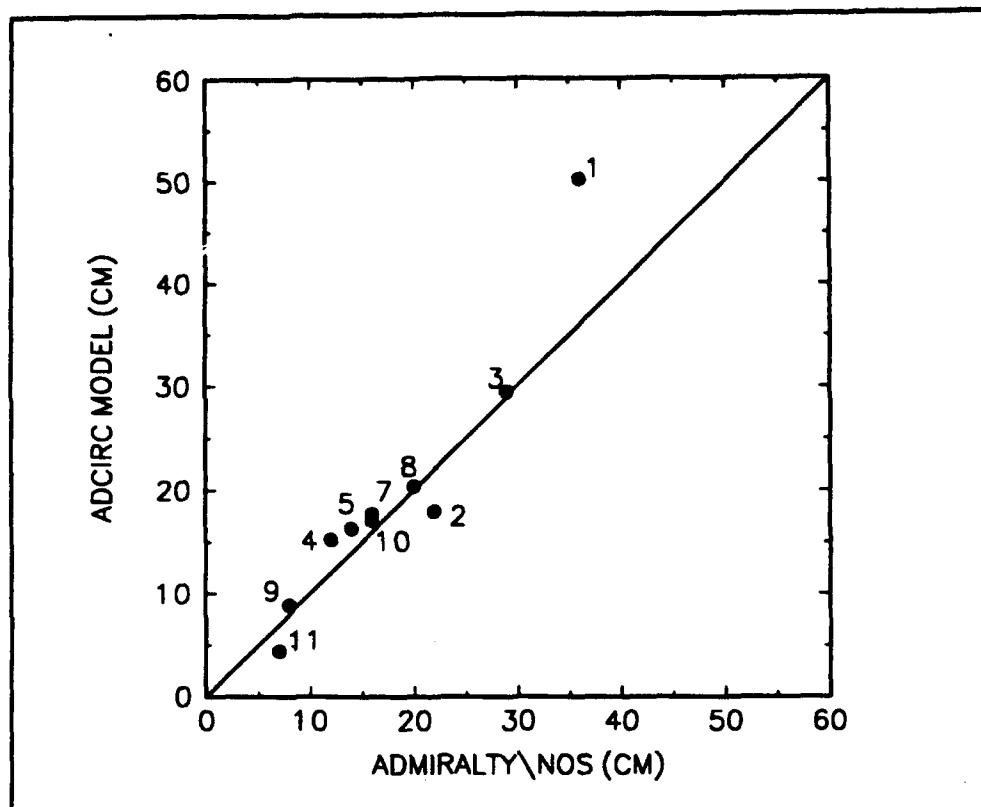


Figure A3. S_2 tidal constituent amplitudes

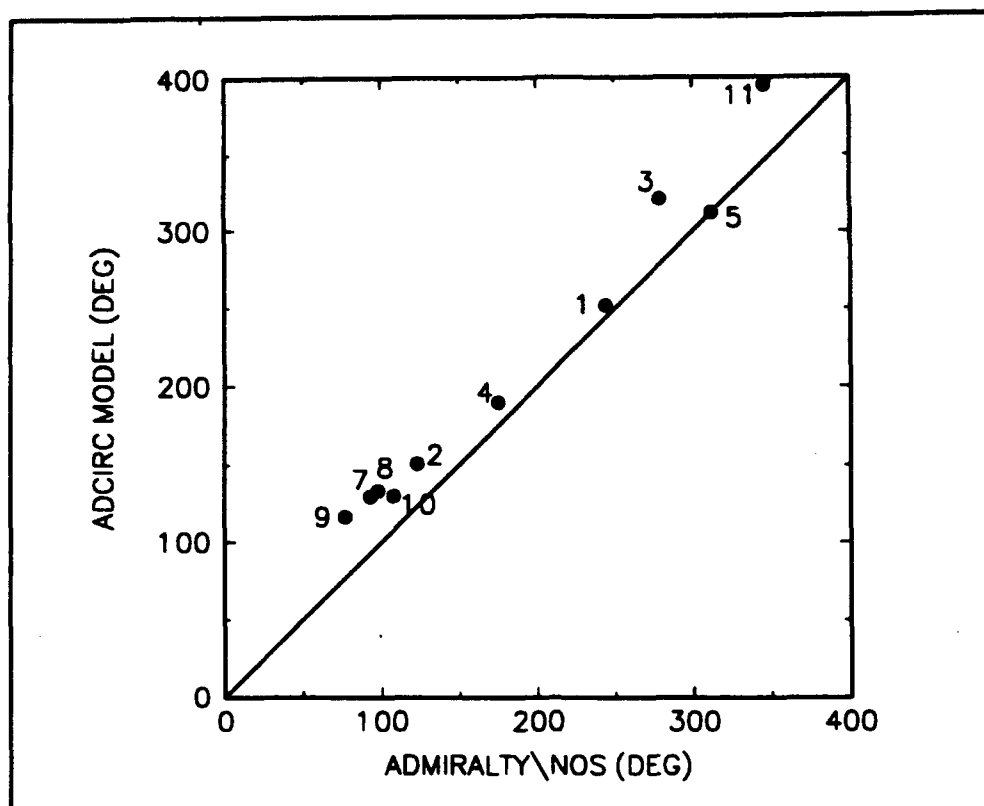


Figure A4. S_2 tidal constituent phases

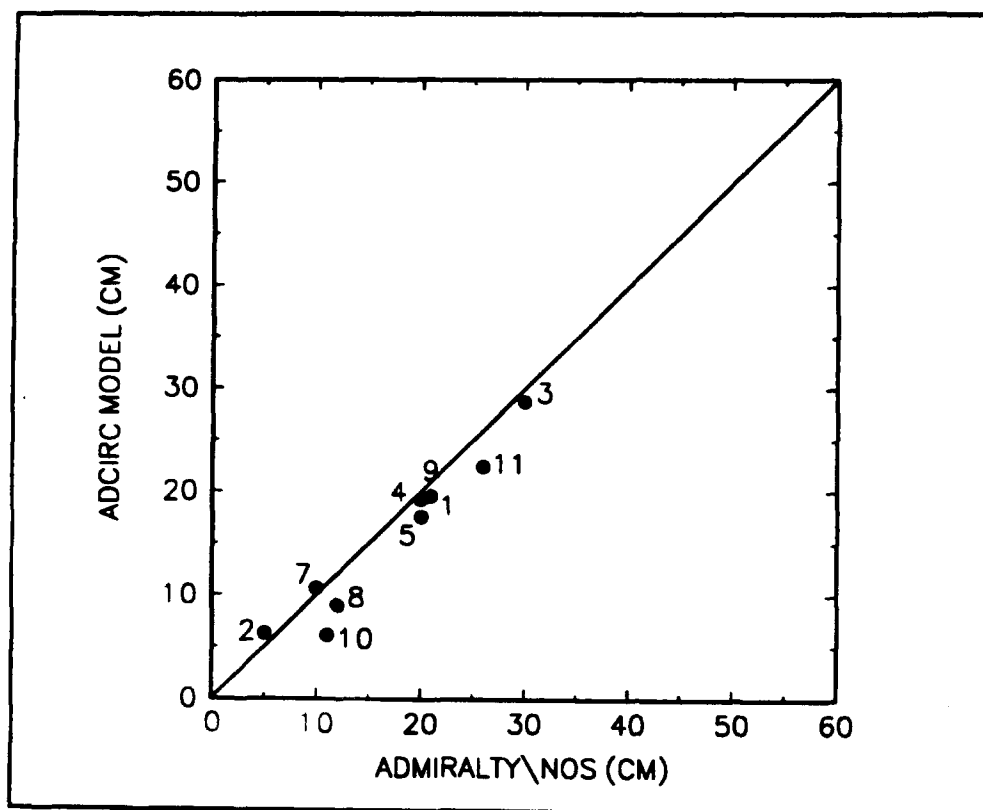


Figure A5. O_1 tidal constituent amplitudes

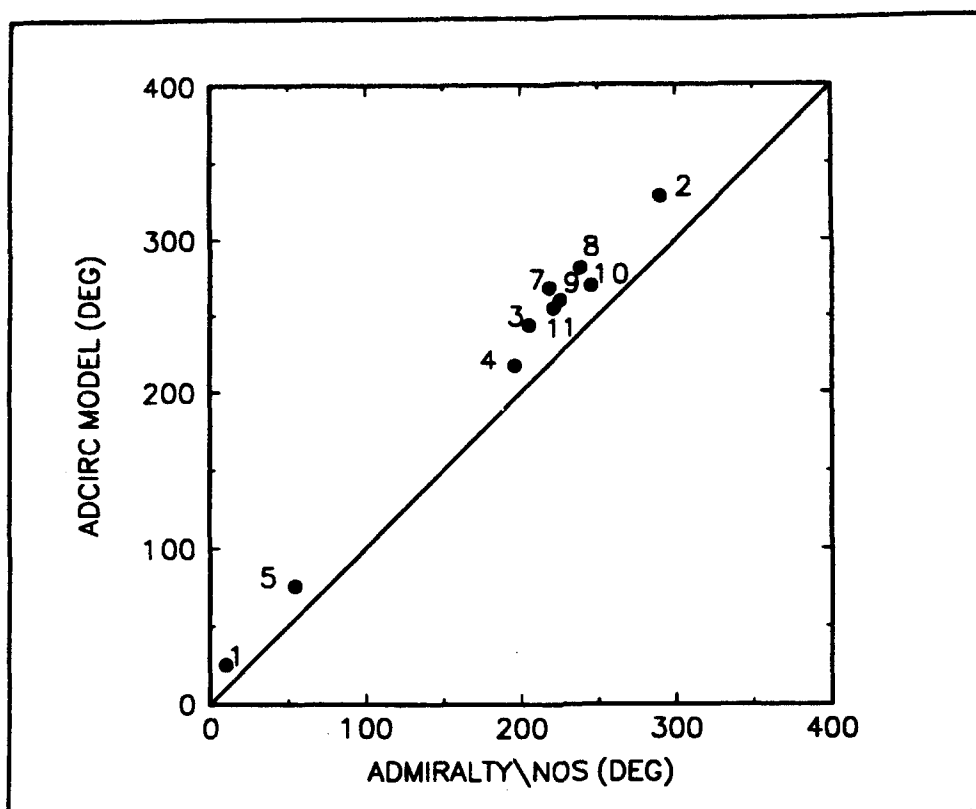


Figure A6. O_1 tidal constituent phases

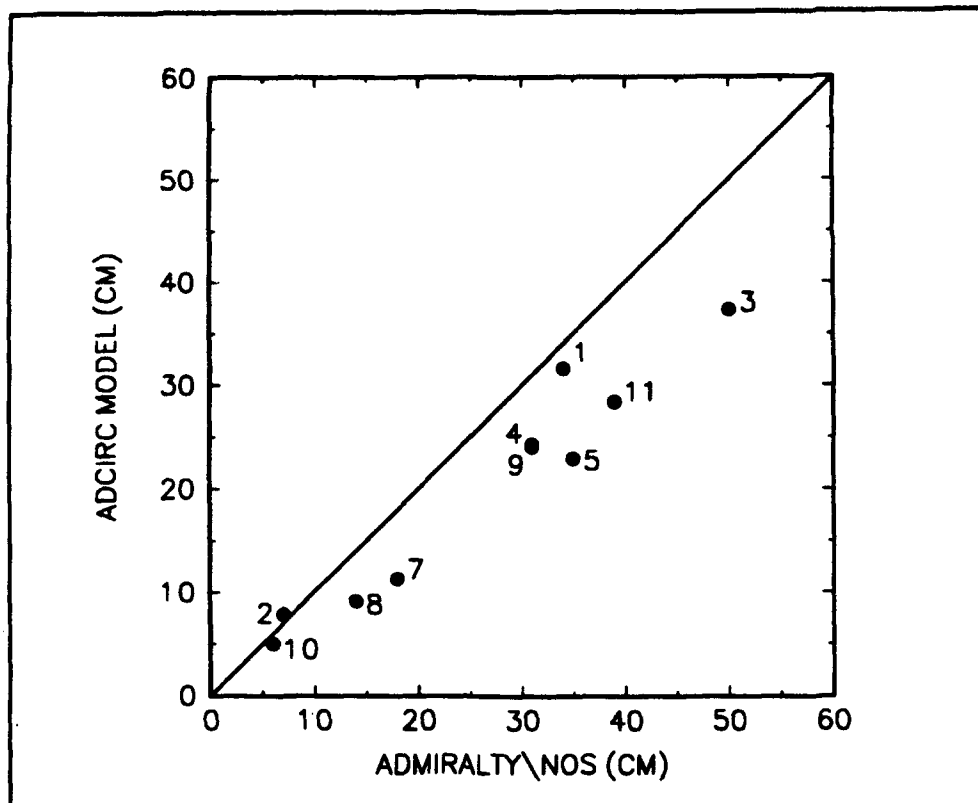


Figure A7. K_1 tidal constituent amplitudes

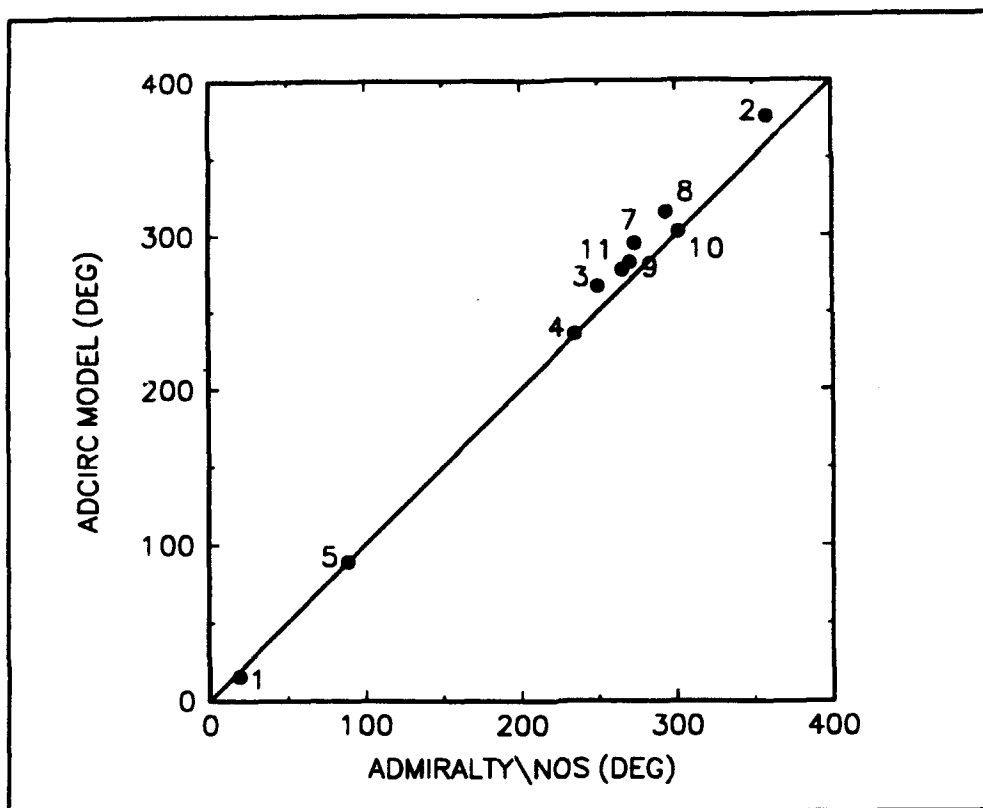


Figure A8. K_1 tidal constituent phases

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13. ABSTRACT (Maximum 200 words) <p>New technology for detailed numerical modeling of water levels and currents at potential LOTS sites is developed and demonstrated in the Persian Gulf and Gulf of Oman. This technology offers great potential for systematically developing large-scale regional models, which are driven by operational global-scale tide and wind models. Nearshore areas of special interest, including complicated areas with shoals, islands, and channels, can be represented with exceptional detail and accuracy (provided bathymetric data are available).</p> <p>The grid used in this study was designed to concentrate resolution in shallow areas or constricted regions where strong flow velocities can be expected. There was no effort to increase resolution at a specific, hypothetical LOTS site. An example LOTS application is discussed in terms of the Iranian coast near the island of Qeshm, where large tides and strong flows are experienced in a confined area. Water levels and currents are estimated with the long-wave hydrodynamic model ADCIRC. The model is applied in the following two ways: (a) force with astronomical tides to create tidal constituent amplitudes and phases for water levels and currents, (b) force with wind field to estimate water level and current response.</p> <p>The model provides information over the entire Persian Gulf as well as detailed information in areas of fine grid resolution.</p>				
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